## ATLAS pp cross section results K.Hiller, DESY

## on behalf of the ATLAS collaboration



## Outline:

- Inelastic rate measurement with MBTS
- Elastic measurements with ALFA



## Detector overview

## MBTS

Minimum Bias Trigger Scintillators

- Count inelastic events
in the fiducial $\eta$-region.
- Calculate in fiducial area $\sigma_{\text {inel }}$.
- Extrapolate to full region.
- Results for 7 TeV, 13 TeV.


## ALFA

## Absolute Luminosity For ATLAS

- Measurement of elastic rate.
- Calculate $\sigma_{\mathrm{el}}$ in small $t$-range.
- Use optical theorem to determine $\sigma_{\text {tot }}$.
- Results for 7 TeV, 8 TeV.



## Interest in total \& inelastic Xsections

Main interests:

- Basic physics quantity - must be measured.
- Needed to normalize Monte Carlo models.
- Mandatory to understand pile-up at LHC.
- Crucial input for simulation of cosmic ray air showers.


## Main problem:

- Not calculable by QCD or other fundamental theories.
- Models predict large spread.
- Values from air shower data have large uncertainties.
- In the high-energy domain precise values came always from colliders: ISR, SPS-collider, Tevatron ...

And now LHC as has taken over this task at maximum collider energies.

## MBTS measurements

- 7 TeV: Nature Commun. 2 (2011) 463.
- 13 TeV: CERN-EP-2016-140 ; arXiv: 1606.02625; submitted to Phys. Rev. Lett.
*** Focus on fresh 13 TeV results ***


## MBTS detector \& data

- Scintillator discs in front of endcap calorimeters, 3.6 m from center.
- New in Run2: $8+8 \rightarrow 8+4$ segments, acceptance slightly extended: $2.07<|\eta|<3.86$.
- Data taking at low beam intensities:

2010: $7 \mathrm{TeV}, \mu=0.007, L=20 \mu \mathrm{~b}^{-1}$ 2015: $13 \mathrm{TeV}, \mu=0.0023, L=60 \mu \mathrm{~b}^{-1}$ with $\mu=$ average interactions per crossing

- Data selection: by hit multiplicity
> Inclusive sample: 2 or more hits
> Single-sided sample: one side 0, other side 2 or more hits.

- Efficiencies:
> $\approx 97-98 \%$ for charged particle detection
> 99.7\% for triggering inclusive events, $97.8 \%$ for single-side events.


## Fiducial cross section

$$
\sigma_{\text {inel }}^{\text {fid }}\left(\xi>10^{-6}\right)=\frac{N-N_{\mathrm{BG}}}{\epsilon_{\text {trig }} \times \mathcal{L}} \times \frac{1-f_{\xi<10^{-6}}}{\epsilon_{\mathrm{sel}}}
$$

Corrections $\approx 1$

- The $\eta$-range $2.07<\eta<3.86$ is sensitive for $M_{x}>13 \mathrm{GeV}$ and defines $\xi_{\text {min }}=M_{x}^{2} / s=10^{-6}$.
- Background is rather low: 1.2\% inclusive, $5.8 \%$ single-sided.
- Migration correction small: $\approx 1 \%$ from various simulations.
- Selection efficiency high: $\approx 99 \%$ based on simulations ( $\xi_{\text {min }}$ at $50 \%$ efficiency)

$$
68.1 \pm 0.6 \text { (exp) } \pm 1.3 \text { (lum) mb }
$$



- Simulations essential for efficiencies \& error estimates \& extrapolation.


## Diffractive fraction

Ratio of single-sided to inclusive events, $\mathbf{R}_{\mathrm{SS}}$, used to constrain diffractive fraction:

$$
f_{\mathrm{D}}=\left(\sigma_{\mathrm{SD}}+\sigma_{\mathrm{SD}}\right) / \sigma_{\text {inel }}
$$

with $\mathrm{SD}=$ single diffraction, $\mathrm{DD}=$ double diffraction

- Measured: $\mathrm{R}_{\mathrm{ss}}=10.4 \pm 0.4 \%$.
- Pythia8 models:

25 \% - 31\% SD + DD;

- EPOS/ QGSJET: default values rather far off.
- Compared to 7 TeV: no strong rise with energy expected, ranges consistent.
- $f_{D}$ essential input for corrections of acceptance and extrapolation.



## Total inelastic cross section

$$
13 \mathrm{TeV}: \sigma_{\text {inel }}=79.3 \pm 0.6(\mathrm{exp}) \pm 1.3 \text { (lum) } \pm 2.5 \text { (extr) } \mathrm{mb}
$$

- Extrapolation based on Phytia8, DL $\varepsilon=0.085$ and 7 TeV ALFA/MBTS results to minimize model impact.
- Uncertainty of extrapolation taken from spread of models.
- Luminosity \& extrapolation are dominant uncertainties.
- Agreement with theoretical models quite good.

$\rightarrow$ slide \#24.


## ALFA measurements

- 7 TeV: Nucl. Phys. B 889 (2014) 486-548.
- 8 TeV: CERN-EP-2016-158; arXiv:1607.06605; submitted to: Phys. Lett. B.
*** Focus on fresh 8 TeV results ***


## Measurement principle

The optical theorem relates the total cross section to the elastic forward scattering:

$$
\sigma_{t o t}=4 \pi \operatorname{Im}\left(F_{e l}(t=0)\right)
$$

$$
\sigma_{t o t}^{2}=\left.\frac{16 \pi}{1+\rho^{2}} \frac{d \sigma_{e l}}{d t}\right|_{t=0}
$$

$$
\rho=\operatorname{Re}\left(F_{e l}\right) / \operatorname{Im}\left(F_{e l}\right)
$$

Key point: measure at very small $t$.
To access small scattering angles:

1) Tracking far from IP close to the beam
2) Special optics with high- $\beta^{*}$ to reduce angular divergence at IP.

Technology at all colliders since ISR:
Movable tracking detectors in Roman Pots.


## What's new at LHC ?

With a special optics one can access the Coulomb-Nuclear-Interference region:

$$
\begin{array}{rlr|r}
\hline \frac{d \sigma}{d t} & =4 \pi(\alpha \hbar)^{2} \frac{G^{4}(t)}{t^{2}} & \leftarrow & \\
& +\sigma_{t o t} \alpha \frac{G^{2}(t)}{t} \exp \left(\frac{-B t}{2}\right)(\rho \cos (\alpha \phi)-\sin (\alpha \phi)) & \leftarrow \text { Interference term } \\
& +\frac{1+\rho^{2}}{16 \pi(\alpha \hbar)^{2}} \sigma_{t o t}^{2} \exp (-B t) & \longleftarrow & \\
& & \text { Hadronic scattering }
\end{array}
$$

with the proton electric form factor $G$, the Coulomb phase $\varphi$, and the ratio $\rho$.

From hadronic scattering: Standard way to get $\sigma_{\text {tot }}$ and the nuclear slope B.

Coulomb \& interference region: Allows to fit in addition luminosity and the $\rho$-parameter.


## Special optics: high- $\beta^{*}$

Standard LHC optics with low $\beta^{*} \approx 0.5 \mathrm{~m}$ has a large angular divergence, which prevents the measurement of sufficient small scattering angles.

To access the Coulomb region $|t| \sim$ few $10^{-4} \mathrm{GeV}^{2}$ angles of a few $\mu$ rad are needed, while $\beta^{*} \sim 0.5 \mathrm{~m}$ results in angular spread on the order of $\sim 40 \mu \mathrm{rad}$.

The smallest reachable $t$-value is given by:

$$
\left|t_{\min }\right|=p^{2} \frac{\varepsilon}{\beta^{*}}\left(\frac{y_{\min }}{\sigma_{y}}\right)^{2}
$$

with beam momentum $p$, emittance $\varepsilon$, envelope function $\beta^{*}$, minimum distance $y_{\text {min }}$ and the beam size $\sigma_{y}$.

The emittance $\varepsilon, \beta^{*}$ and detector positions $y_{\text {min }}$ need to be optimized for small $t$.
Optics development steps: $\beta^{*}=90 \mathrm{~m} \rightarrow 1 \mathrm{~km} \rightarrow 2.5 \mathrm{~km}$.
This talk is about results from 90 m data only.

## ALFA setup



4 stations with 8 detectors at both sides of ATLAS provide 2 independent "elastic" arms.

## Stations in the tunnel



## ALFA tracking detectors

## Design principle



## Real detector



- Main detectors (MD): $2 \times 10$ layers of $0.5 \times 0.5 \mathrm{~mm}^{2}$ square fibers.
- Read out by Multi-Anode-Photomultilipliers with 64 channels.
- Light yield 4-5 photo-electrons per fiber.
- Measured resolution ~ $35 \mu \mathrm{~m}$.
- Special overlap detectors (OD) to measure the distance.


## From tracking to $t$-value

Propagation of particles from IP to Roman Pots described by a transport matrix (defined by LHC magnet lattice):

$$
\binom{X}{\theta_{x}}=\left(\begin{array}{ll}
M_{11} & M_{12} \\
M_{21} & M_{22}
\end{array}\right)\binom{X^{*}}{\theta_{x}^{*}}
$$

Due to constraints for vertex and scattering angles the scattering angle at $\theta_{x}{ }^{*}$ can be reconstructed by 4 different methods.
"Subtraction method" with best $t$-resolution:

$$
\theta_{y}^{*}=\frac{y_{A}-y_{C}}{M_{12 A}+M_{12 C}}=\frac{y}{L_{e f f y}}
$$

From $\theta^{*}$ one gets: $t=-\left(p \theta^{*}\right)^{2}$

Elastic track patter in a station:


Typical vertical shape due to high- $\beta^{*}$ optics with $L_{\text {effy }} \gg L_{\text {effx }}$.

## Event selection



For analysis 3.8 million elastic events selected.

## Elastic cross section



## Cross section fit

- Fit theoretical prediction to data.
- Nuclear term dominates, but Coulomb and interference terms included.
- Fit range: $0.014 \mathrm{GeV}^{2}<t<0.1 \mathrm{GeV}^{2}$ (lower bound defined by acceptance, upper to ensure single exponential).
- Dominant errors:
- Luminosity uncertainty $1.5 \%$
- Beam energy 0.65\%
- Extrapolation to $t=0$ (various models).

(b)


## Results:

$$
\begin{aligned}
\sigma_{\text {tot }} & =96.07 \pm 0.18 \text { (stat.) } \pm 0.85 \text { (exp.) } \pm 0.31 \text { (extr.) } \mathrm{mb} \\
B & =19.74 \pm 0.05 \text { (stat.) } \pm 0.16 \text { (exp.) } \pm 0.15 \text { (extr.) } \mathrm{GeV}^{-2}
\end{aligned}
$$

## $\sigma_{\text {tot }}$ evolution with $\sqrt{s}$



## Comparison with TOTEM




- TOTEM can measure the inelastic rate by the T1/T2 telescopes $\rightarrow 3$ methods for $\sigma_{\text {tot }}$.
- ALFA in general lower than TOTEM results, at $8 \mathrm{TeV} \approx 7 \mathrm{mb}$.
- Difference $1.3 \sigma$ and $1.9 \sigma$ at 7 TeV and 8 TeV , respectively.
- Smaller errors for ALFA mainly based on more precise luminosity values.


## B-slope evolution with $\sqrt{s}$



- General trend of increase with $\sqrt{s}$ continues.
- Larger TOTEM slopes result in a corresponding larger $\sigma_{\text {tor }}$.


## Elastic \& inelastic Xsections

The elastic cross section results from the integral over the exponential fit function:

$$
\begin{aligned}
& \sigma_{\mathrm{el}}=\frac{\sigma_{\mathrm{tot}}^{2}}{B} \frac{1+\rho^{2}}{16 \pi(\hbar c)^{2}} \\
& \sigma_{\mathrm{el}}=24.33 \pm 0.04(\text { stat. }) \pm 0.39 \text { (syst.) } \mathrm{mb}
\end{aligned}
$$

By subtraction of $\sigma_{\text {el }}$ from $\sigma_{\text {tot }}$ one obtains $\sigma_{\text {inel }}$ :

$$
\sigma_{\text {inel }}=71.73 \pm 0.15(\text { stat. }) \pm 0.69(\text { syst. }) \mathrm{mb}
$$

All errors at the order of $1 \%$ or below.

Measurements at 8 TeV with smaller errors than 7 TeV results due to more precise luminosity and a larger data sample.

## $\sigma_{\text {inel }}$ evolution with $\sqrt{s}$

|  | 7 TeV | 8 TeV | 13 TeV | Comments |
| :--- | :--- | :---: | :---: | :--- |
| MBTS | $69.1 \pm 7.3 \mathrm{mb}$ |  | $79.3 \pm 2.9 \mathrm{mb}$ | Main error contribution extrapolation |
| ALFA | $71.3 \pm 0.9 \mathrm{mb}$ | $71.7 \pm 0.7 \mathrm{mb}$ |  | Small errors due to precise lumin. |
| TOTEM | $72.9 \pm 1.5 \mathrm{mb}$ | $74.7 \pm 1.7 \mathrm{mb}$ |  | Based on elastic \& inelastic rates |
| CMS |  |  | $71.3 \pm 3.5 \mathrm{mb}$ | Preliminary, based on HF calorimeters |



- In general increase with $\sqrt{s}$ visible as expected.
- Values at 7 TeV and 8 TeV agree within errors.
- At 13 TeV some discrepancy, but large errors.


## Summary \& outlook

## MBTS:

- Inelastic cross section at 7 TeV and 13 TeV measured.
- Improved precision at 13 TeV due to extended $\xi$-range, and more precise luminosity.


## ALFA:

- Total, elastic and inelastic cross sections at 7 TeV and 8 TeV measured.
- Analysis of $8 \mathrm{TeV} @ \beta^{*}=1 \mathrm{~km}$ and $13 \mathrm{TeV} @ \beta^{*}=90 \mathrm{~m}$ ongoing.


## Future plans:

- Data taking at $13 \mathrm{TeV} @ \beta^{*}=2.5 \mathrm{~km}$ in preparation, potential to measure $\rho$ and luminosity from data in the CNI region.
- Continue measurements up to maximum LHC energy.


## Backup slides

## Consistency of results

From elastic data constraints for the transport matrix elements can be derived. The four methods to reconstruct the scattering angle at IP allow fine tuning of magnets.

Corrections for field strength of inner triplet Q1-Q3: $\approx 2.5 \%$.

| Constraint | Value | Stat. | Syst. | Total |
| :---: | :---: | :---: | :---: | :---: |
| $\Delta \mathrm{kQ}_{1} \mathrm{Q}_{3} \mathrm{~B} 1 \%^{\circ}$ | 2.21 | 0.03 | 0.13 | 0.14 |
| $\Delta \mathrm{kQ}_{1} \mathrm{Q}_{3} \mathrm{~B} 2$ \%o | 2.90 | 0.03 | 0.25 | 0.25 |

The effective optics ensures the consistency of different reconstruction methods:

|  |  |  |  | $\sigma_{+5+}[\mathrm{mb}]$ |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Subtraction | Local angle | Lattice | Local subtraction |  |  |
| Total cross section | 96.07 | 96.52 | 96.56 | 96.58 |  |  |
| Statistical error | 0.18 | 0.15 | 0.16 | 0.15 |  |  |
| Experimental error | 0.85 | 0.94 | 0.88 | 0.89 |  |  |
| Extrapolation error | 0.31 | 0.42 | 0.23 | 0.23 |  |  |
| Total error | 0.92 | 0.98 | 0.93 | 0.93 |  |  |

